Ionization Physics at Extreme Intensity

D.F. Gordon, B. Hafizi, J. Palastro, D. Kaganovich, M.H. Helle, Y.-H. Chen, L. Johnson, R.F. Hubbard, A. Ting

Naval Research Laboratory, Plasma Physics Division, Washington DC

Workshop on High Energy Density Physics with BELLA-i

LBNL, January 20, 2016

Work Supported by NRL 6.1 Base Funds

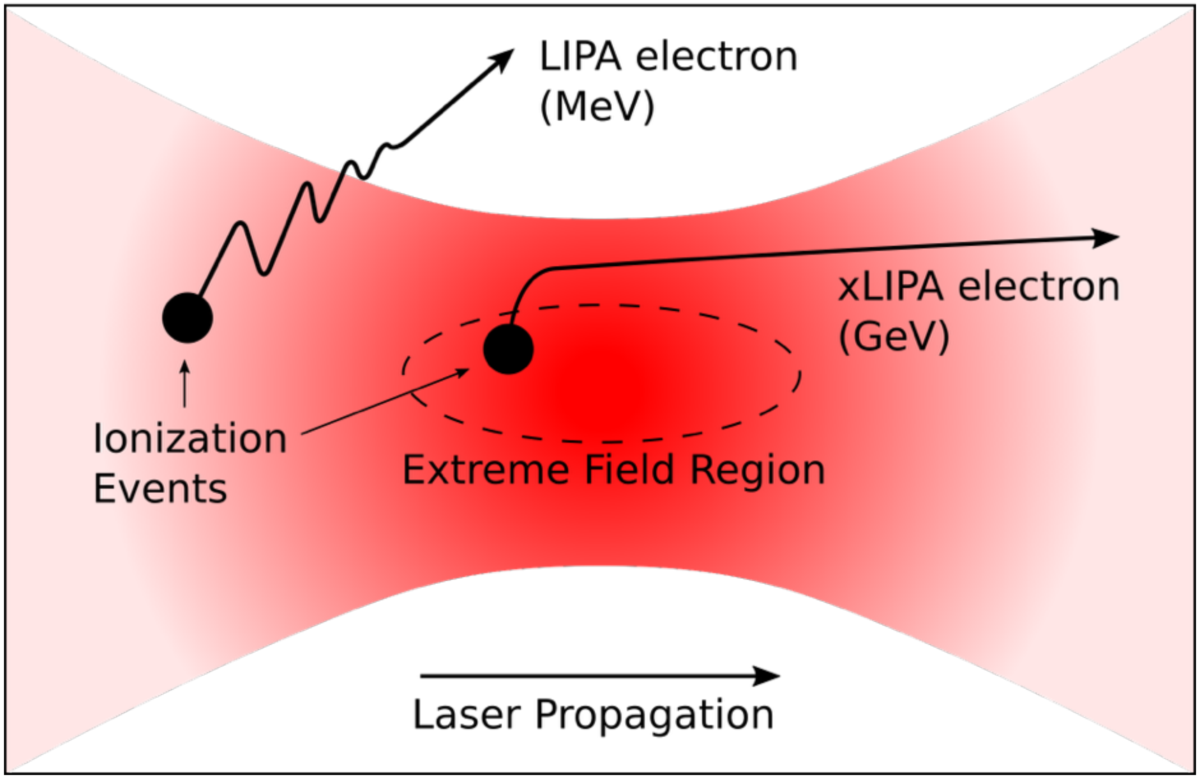
Outline

- Background : novelty of "high field physics" in "extreme fields"
- What we expect to see
  - Electron distributions from uniform gas
  - Electron distributions from single atoms
  - Radiation reaction (not in the near term!)
- Targets
  - Targets that load the whole confocal region
  - Targets that simulate single-atom distribution

Ultrarelativistic Bound-Free Transitions (xLIPA)

NRL PPD

Gas Filled Box. Density kept low to minimize plasma physics.



In a plane wave, accelerated electrons satisfy an energy-angle relationship:

$$\tan \theta_\gamma = \sqrt{\frac{2}{\gamma - 1}}$$

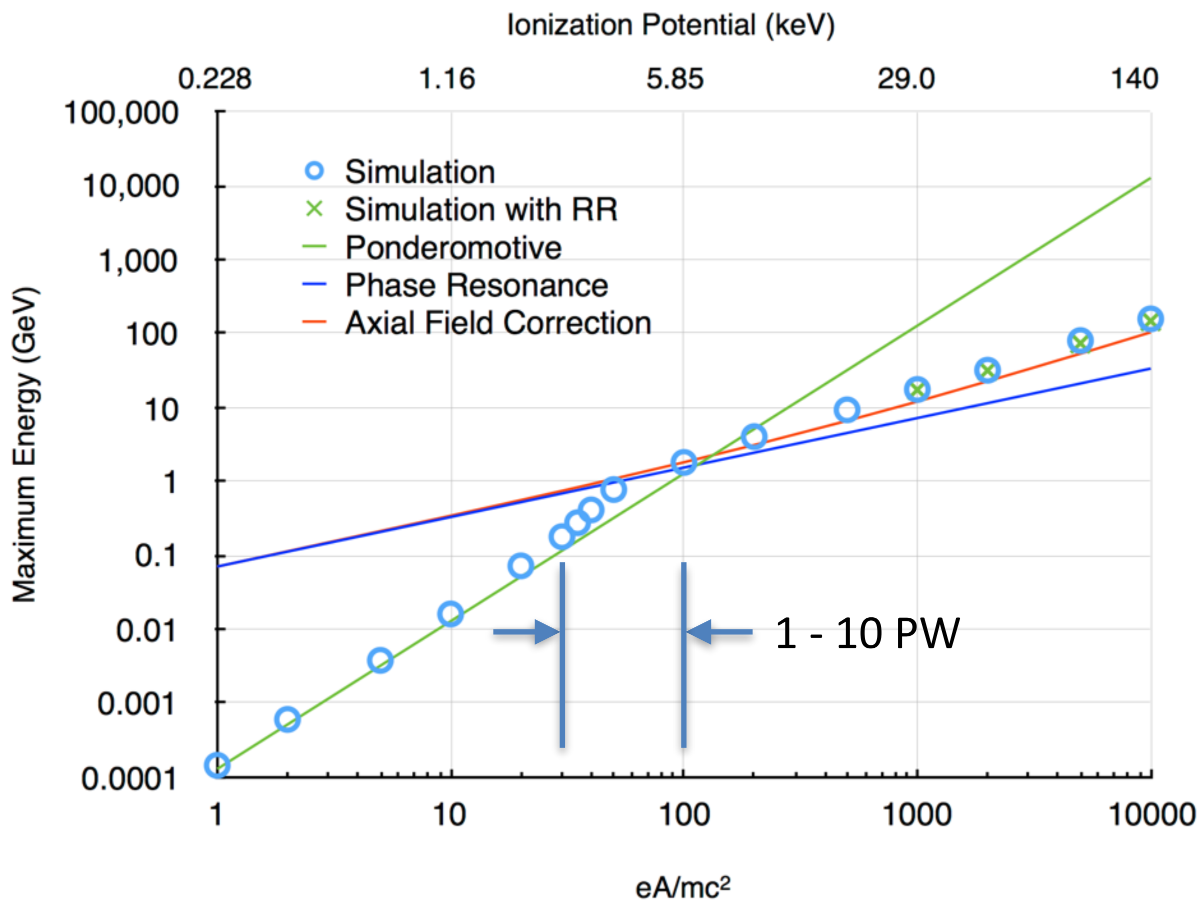
Relation can be broken in case of tight focusing

Conventional LIPA Refs:

1. C. Moore et al., Phys. Plasmas 8, 2481 (2001)
2. A. Ting et al., Phys. Plasmas 12, 010701 (2005)

Transition from LIPA regime to xLIPA regime

- multi-PW pulses access a new regime of free space acceleration
- Phase resonance leads to **super-ponderomotive** scaling



All results with 5 um spot and 0.8 um radiation

Theory of xLIPA (ultra-relativistic limit)

Assume a phase resonant trajectory exists (field tensor slowly varying on world line).
To get a simple formula neglect the axial field.

$$\gamma_{\max} = 1 + 2\left(\frac{3\pi r_0}{\lambda}\right)^{2/3}\left(\frac{P r_e}{m c^3}\right)^{1/3}$$

P = laser power
r_0 = spot size
r_e = classical electron radius

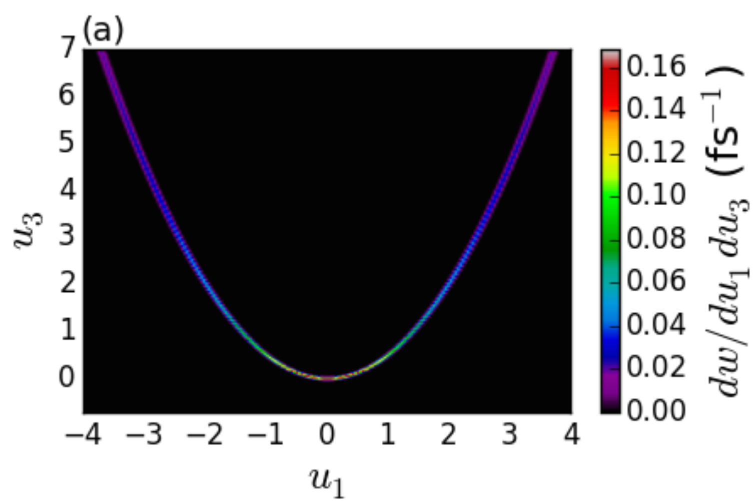
- No advantage in varying laser wavelength for given f#
- Axial fields cause $P^{1/3}$ scaling to go over to $P^{1/2}$ scaling
- Analysis valid when photoelectrons are accelerated to speed of light "abruptly enough." Based on simulation, this is when $a > 100$.

Ordinary vs. Extreme Ionization Physics

- multi-PW pulses produce remarkable photoelectron distributions
- Discrete features appear that can be associated with sub-cycle dynamics (a controversial notion in strong field physics)

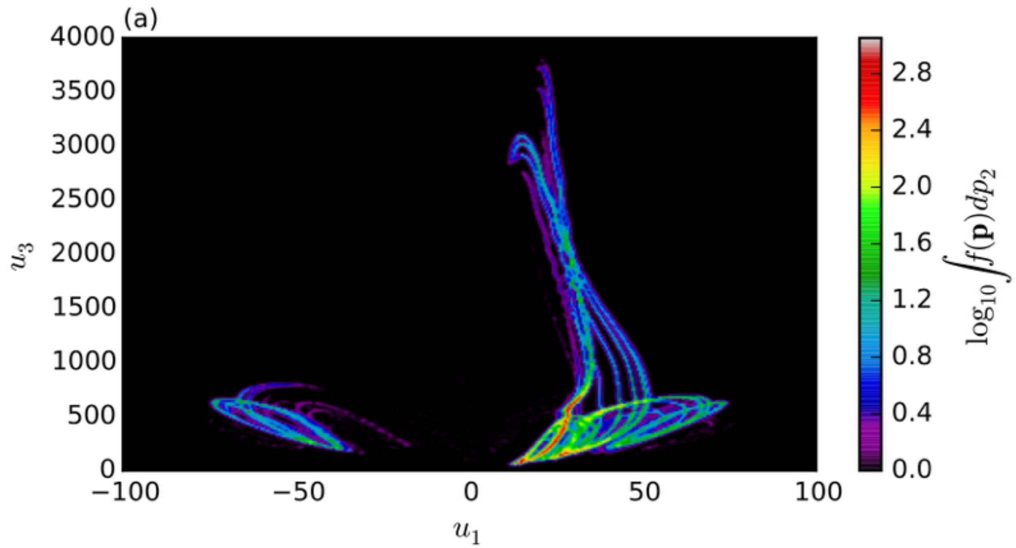
u = p/mc
1=polarization
3=propagation

Analytical SFA Prediction, 10^{21} W/cm^2
(plane wave)



The SFA gives a parabola in all cases

Simulation, 10^{22} W/cm^2
(~f/5 focusing)



- Asymmetry due to initial position of atom
- Highest energies due to phase resonance

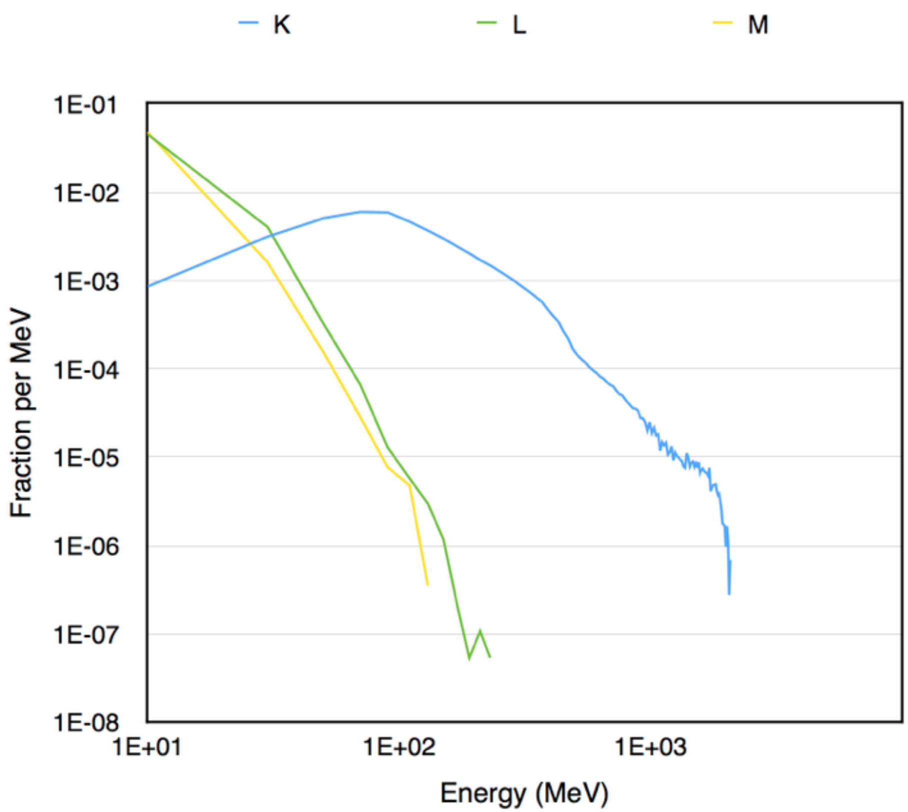
What will we see?

Electron Distributions from uniform gas
Electron distributions from localized atoms

(Adapted from 10 PW ELI-NP briefing ; must re-calculate for ~1 PW)

Electron spectra from uniform argon gas

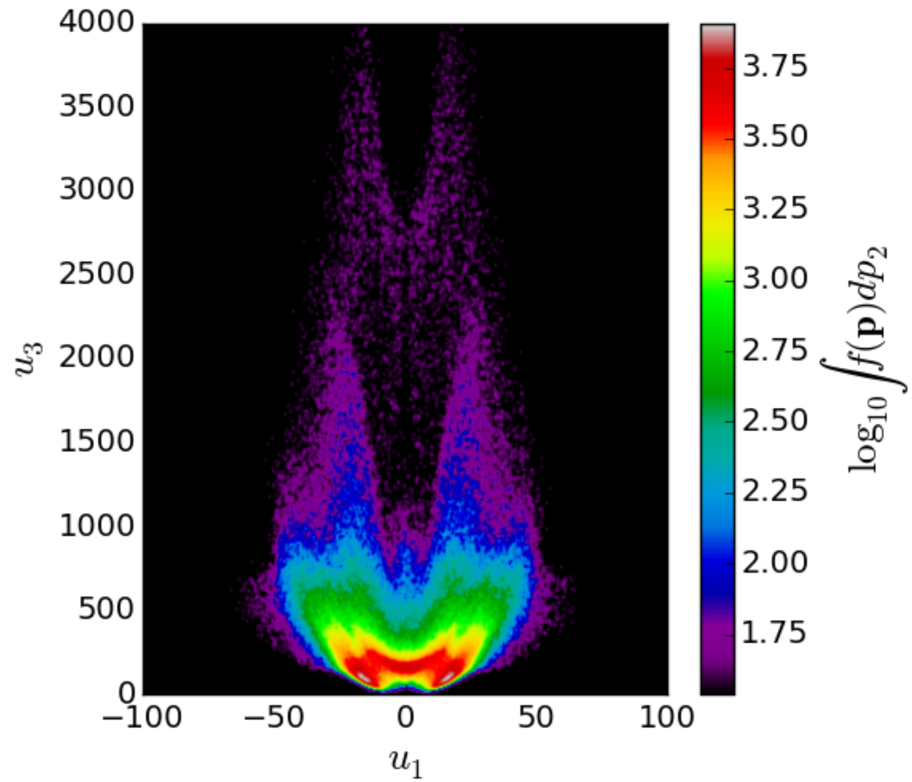
10 PW , a=100 , r_0 = 5 µm , spectra integrated over all angles



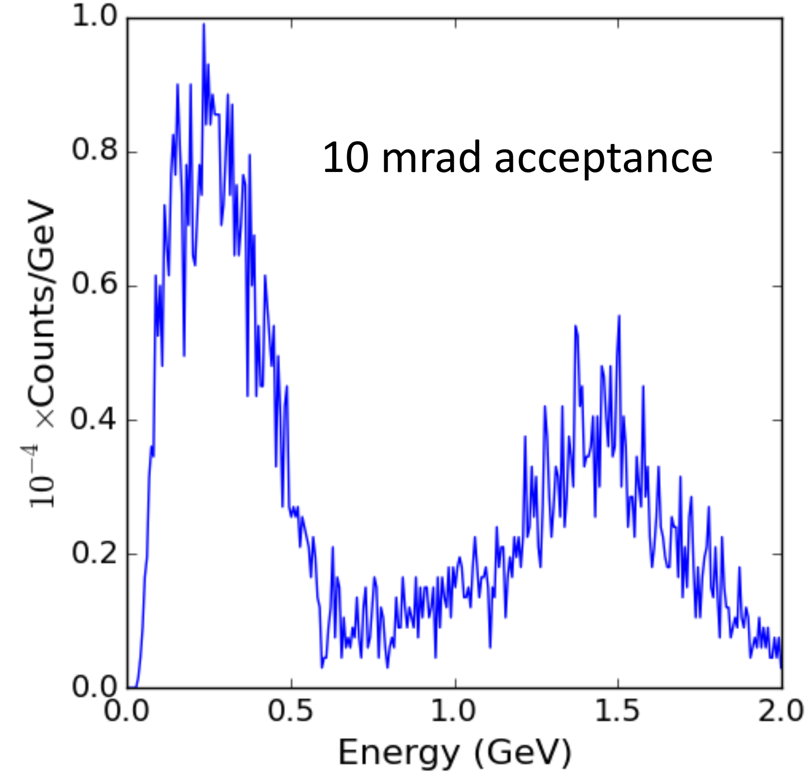
- Coulomb corrected, fully relativistic SFA rate law
- Advanced, high-fidelity, particle pusher
- Spectra are for tightest binding per shell

K shell spectrum easily identifiable

Phase space and finite-acceptance spectrum in uniform argon



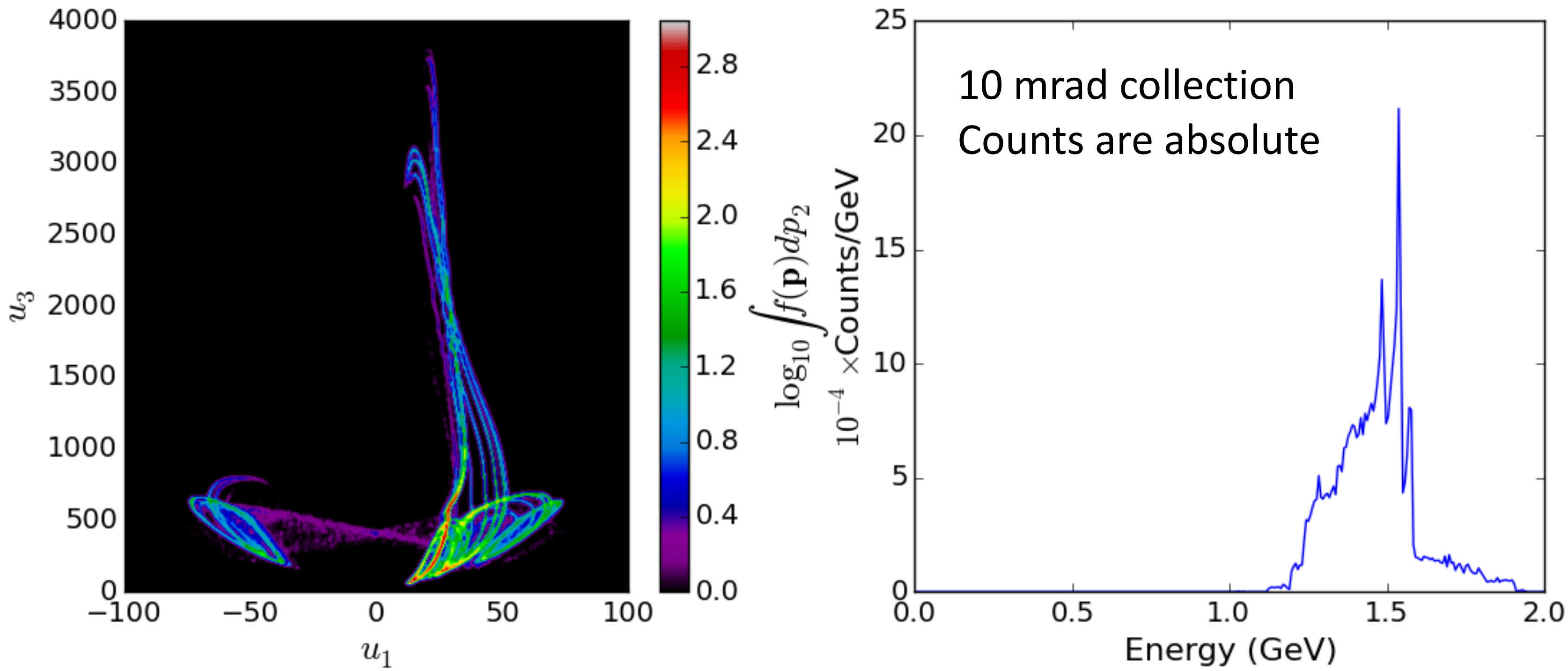
atomic density ~ 10^{12} cm^{-3}



- Expect to collect ~$10^{-8}n$[cm^{-3}] electrons (10^{17} gives 100 pC)
- About half at 100 MeV, half at 1.5 GeV
- Full collection gives ~100 times more, peaked at 100 MeV

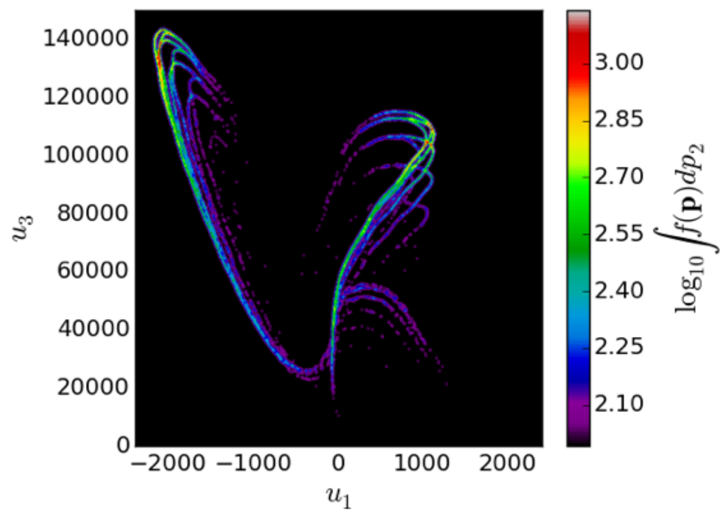
K-shell electrons from a 10 nm radius argon cluster

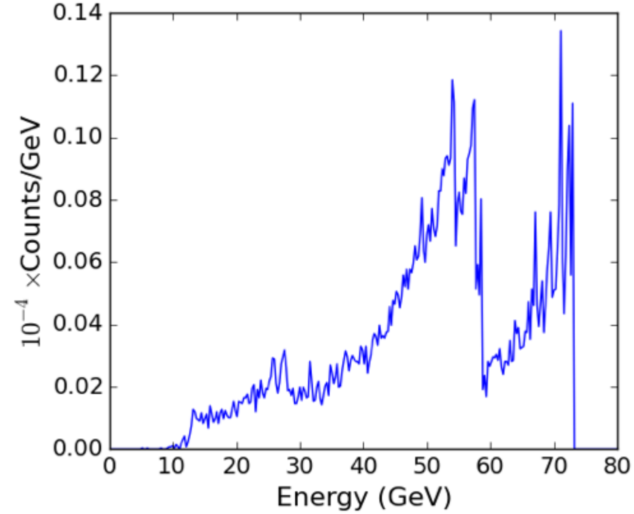
- Distribution sensitive to initial position
- Here the cluster is at r = r_0 and z = $-2z_R$



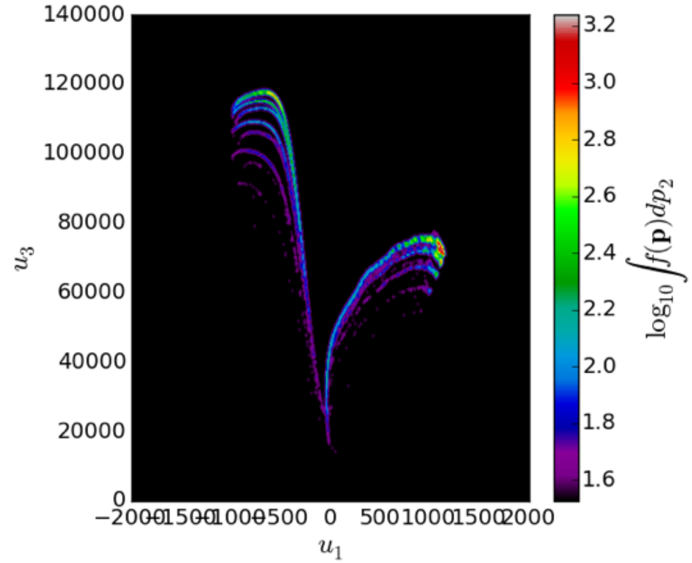
25 Exawatt illumination of gold nanoparticles including radiation reaction effects (as an interesting aside)

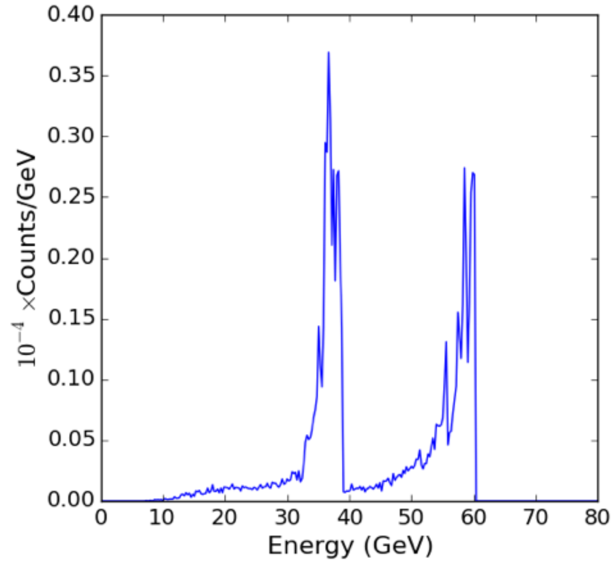
Neglecting RR





Including RR





Targets

Uniform targets

Localized targets

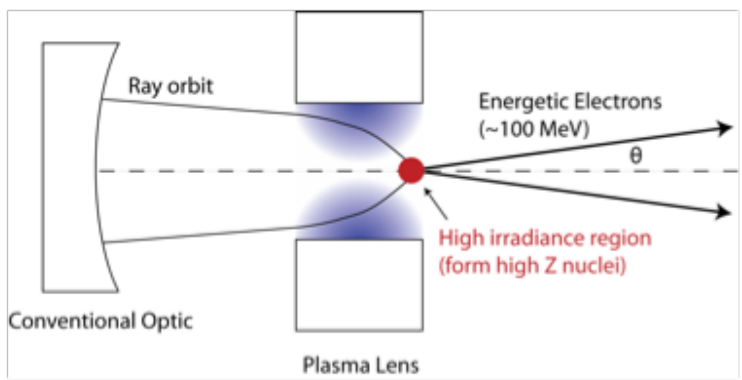
Target Design Issues

NRL PPD

- Prepulses may spoil focusing into certain targets
- Prepulses may spoil localization of atoms with certain targets
- Low density preferred to avoid laser propagation issues
- K-shell electrons do not care about neighboring atoms, even at solid density (K-shell binding energy >> lattice binding energy)
- Localized but random positioning of atoms possible with cluster jet?
  - Diagnostics needed to determine position a posteriori
- Argon could be replaced with titanium nanoparticles
  - How to introduce into laser focus?

Original idea was to use a plasma lens target*

- F/20 focus into short plasma channel (plasma lens)
- Plasma lens does ***not*** provide additional focusing for laser powers beyond about 1 PW
- Still may be useful to generate low densities suitable for xLIPA, but short focal length parabola must be used
- Could spoil focusing if density too high



* J.P. Palastro et al., Phys. Plasmas **22**, 123101 (2015)

Alternatives to plasma lens

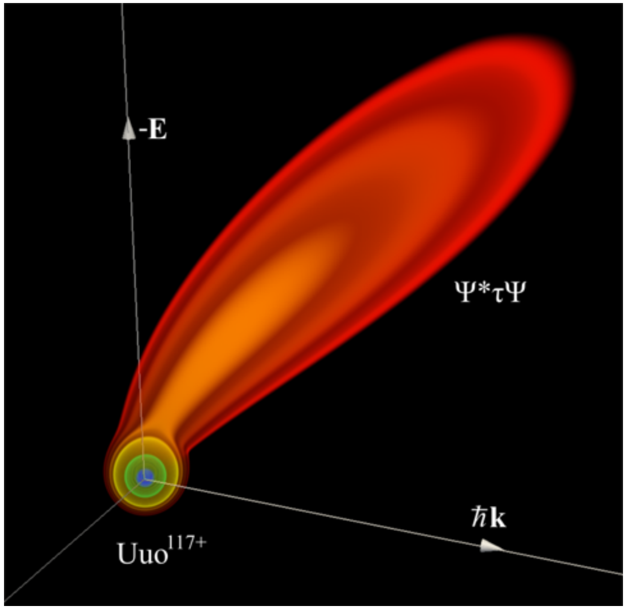
- Use a simple argon gas jet
  - Run at lowest possible density
  - Focus in density up-ramp
  - Limit length to discourage LWFA
- To achieve lower density use a cluster jet
  - Requires cryogenic cooling
  - Spectacular results possible if single cluster illumination can be arranged
  - Prepulses may spoil localization
- Illuminate titanium nanoparticles or foils
  - Some research likely needed regarding nanoparticle acquisition, delivery into laser focus, etc..
- Plasma jets

BACKUPS

Additional Viewgraphs

Relativistic Ionization

- Lately relativistic tunneling theories and ab initio simulations are becoming available*
- Quantum mechanical models cannot follow the electron out of the laser field except in plane wave case
  - Therefore resort to two-step ionization model
  - Requires particle tracking in extreme fields <u>which is not trivial</u>

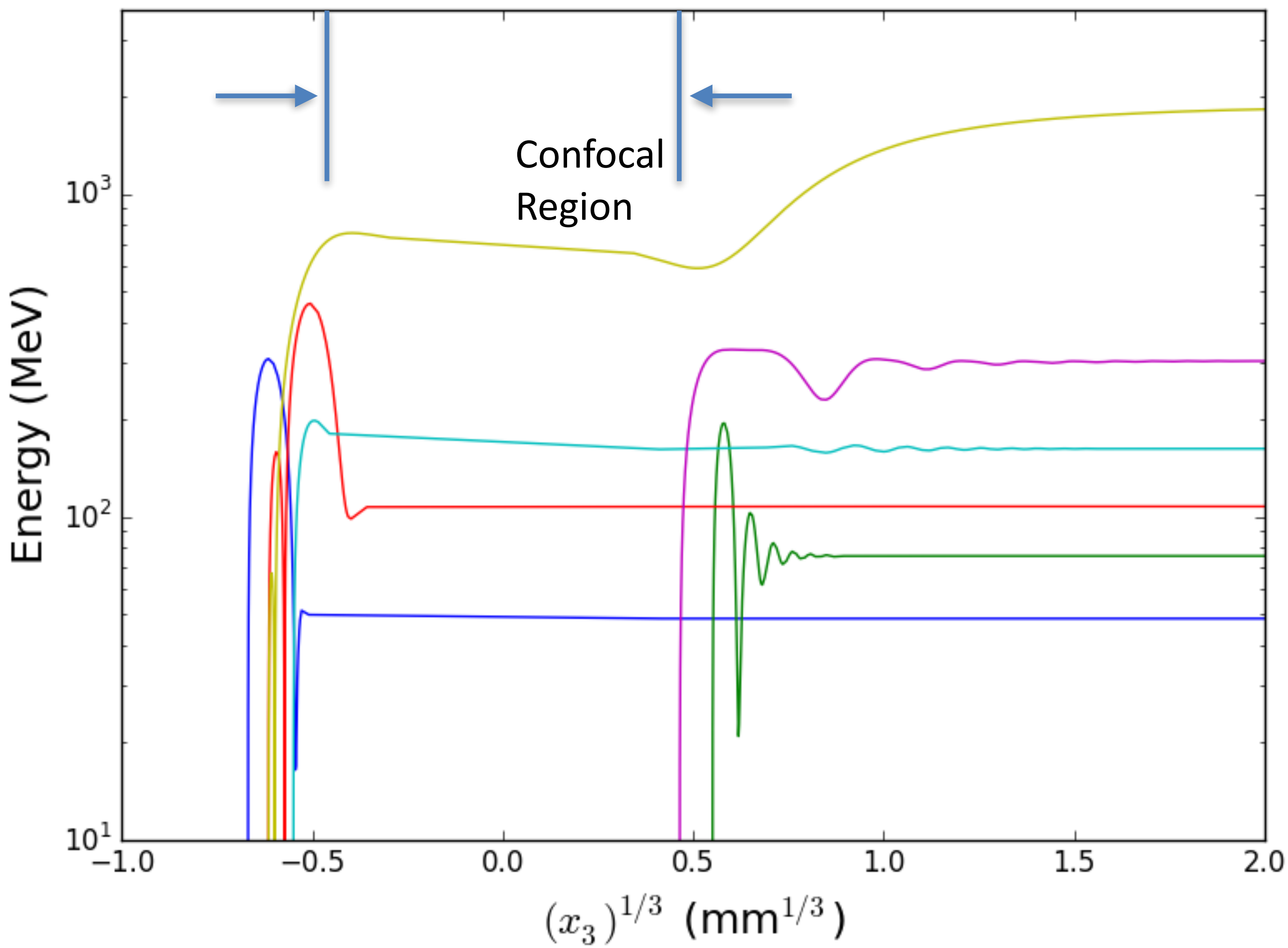


Ab initio calculation of an ionizing wavefunction, in the case of a superheavy ion, using NRL turboWAVE-QO.

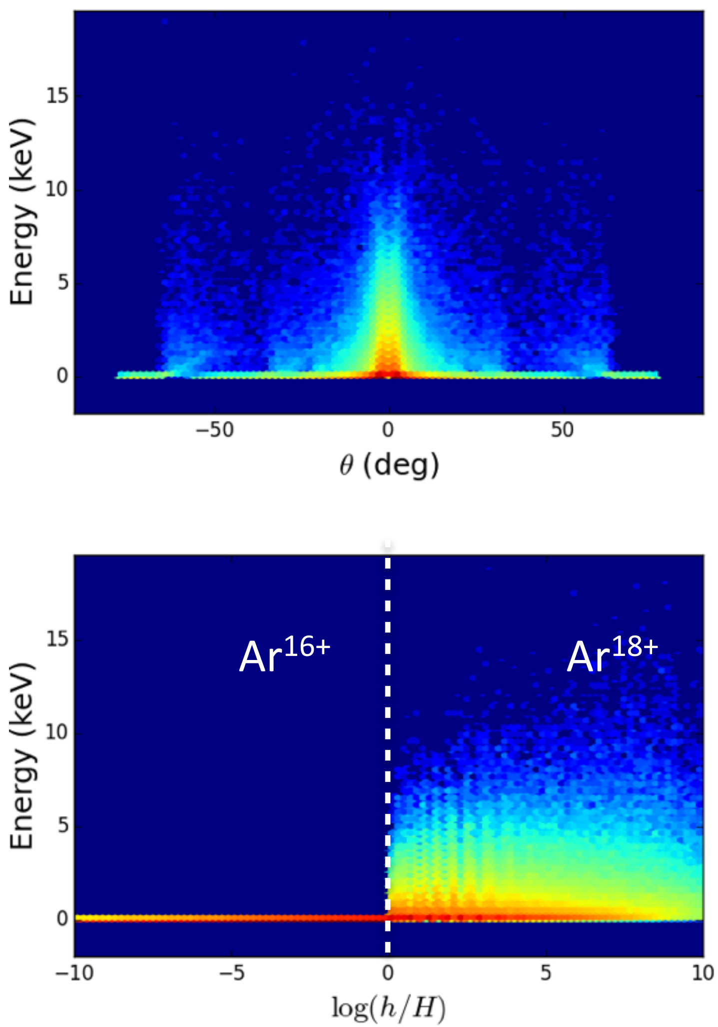
(Perhaps the first such calculation in three dimensions)

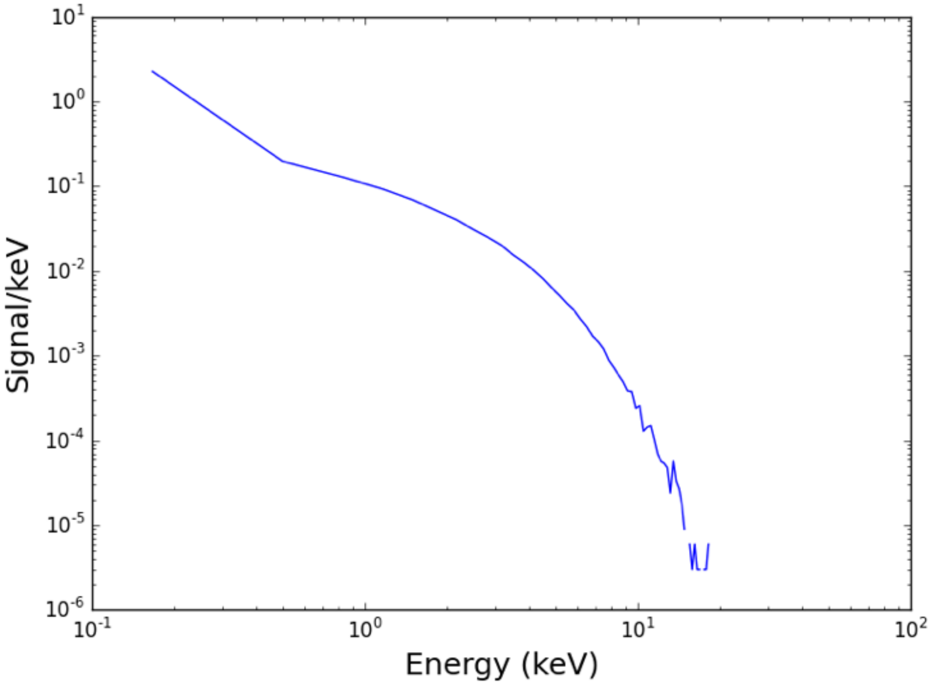
*M. Klaiber et al., Phys. Rev. A 87, 023418 (2013); D.F. Gordon et al., J. Comp. Phys. 267, 50 (2014)

xLIPA : Typical Orbits



Argon nuclei are slightly accelerated by laser fields





Only bare nuclei gain significant energy

Argon Nuclei from Laser Tunneling

NRL PPD

Threshold Intensities

Coulomb-corrected relativistic SFA [1] and BSI [2] Models

Shell	Electrons	Maximum Potential	Coulomb-SFA	BSI
		(eV)	(W/cm^2)	(W/cm^2)
M	8	143	$1.3x10^{17}$	$2.7x10^{16}$
L	8	918	$2.5x10^{19}$	$1.1x10^{19}$
K	2	4426	$2.3x10^{21}$	$4.8x10^{21}$

1. M. Klaiber et al., Phys. Rev. A 87, 023418 (2013)
2. S. Augst et al., Phys. Rev. Lett. 63, 2212 (1989)